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MEASUREMENTS OF THE STATIC PRESSURE DISTRIBUTIONS AND SHOCK SHAPE ON AN OBLATE SPHEROID AT MACH NUMBERS OF 3 and 6

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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Aerodynamics Research Report No. 265

MEASUREMENTS OF THE STATIC PRESSURE DISTRIBUTIONS AND SHOCK SHAPE ON AN OBLATE SPHEROID AT MACH NUMBERS OF 3 AND 6

by

Lionel Pasiuk

ABSTRACT: The results of experimental measurements of the static pressure distribution and bow sh ck shape on an oblate spheroid are presented. This experiment was conducted at nominal Mach numbers of 3 and 6 and a free stream Reynolds number range of 2.3×10^6 to 5.8×10^6 per foot. Comparisons are made with the calculated values of several different laboratories.

U. S. Naval Ordnance Laboratory
White Oak, Silver Spring, Maryland

5 July 1966

Measurements of the Static Pressure Distribution and Shock Shape on an Oblate Spheroid at Mach Numbers of 3 and 6

This report presents the results of an experimental project at the request of the Office of Naval Research. In a separate program the Office of Naval Research had found that analytical results, performed at various laboratories, gave widely diffferent results for the pressure distribution and shock shape on a blunt body in supersonic flow. The purpose of the present experiments was to identify which analytical prediction was correct.

The experiments were carried out in Supersonic Tunnel No. 2 and the Hypersonic Tunnel at the U. S. Naval Ordnance Laboratory.

J. A. DARE
Captain, USN
Commander

K. R. ENKENHUS
by direction

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ILLUSTRATIONS

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SYMBOLS

a	major axis of the oblate spheroid
B	bluntness parameter of the oblate spheroid, $B = (a/b)^2$
b	minor axis of the oblate spheroid
D	model base diameter
M	Mach number
P	dimensionless pressure, $P = p/\rho_\infty u_\infty^2$
p	pressure
p_o	supply pressure
R	coordinate normal to the flow
R_c	model radius of curvature at the stagnation point
Re_D	Reynolds number based on model diameter, $Re_D = \rho_\infty u_\infty D/\mu_\infty$
r	nondimensional coordinate normal to the flow, $r = R/R_c$
T_o	supply temperature
u_∞	free stream velocity
Z	coordinate in the flow direction
Z_M	measured Z coordinate of the model
z	nondimensional coordinate in the flow direction, $z = Z/R_c$
μ_∞	absolute viscosity in the free stream
ρ_∞	density in the free stream
ϕ	roll angle

INTRODUCTION

Comparisons of various numerical calculations of the detached shock flow field about a series of blunt bodies were made at the Naval Weapons Laboratory under the sponsorship of the Office of Naval Research. Calculations were performed by several government and private laboratories on ellipsoids of revolution of various degrees of bluntness. Details of these methods and the results of the calculations are given in reference (1). This report contains the results of surface pressure and detailed shock wave measurements on one of these bodies and compares the experimental results with the corresponding numerical calculations

EXPERIMENTS

Model

The model is an oblate spheroid. A sketch is given in Figure 1 and a photograph in Figure 2. To make the photograph a mirror was placed behind the model so that both its front and back may be seen. Its degree of bluntness B, is defined as the ratio of its major to minor axis squared,

$$B = (a/b)^2$$

and for this model B = 4. Both the maximum diameter D, and the radius of curvature at the stagnation point R_c, have values of 4 inches. The contour is given by the following equation,

$$r = 2[z(2-z)]^{\frac{1}{2}}$$

when the origin is taken as the stagnation point. This contour is continued in the base region.

There are 24 pressure orifices on the model, each with a diameter of 0.030 inches. The location of these orifices is given in the table in Figure 1.

The model's original surface finish was 32 microinches, and this finish remained the same through the $M \cong 3$ test in Supersonic Tunnel No. 2. But during the test in the Hypersonic Tunnel at $M \cong 6$, the surface finish became very rough on the windward half of the model and this roughness is now measured to be from 60 to 85 microinches.

Both the model and pressure tubing are made from stainless steel. The tubes are connected to the model with high temperature silver solder.

Test Facilities

These tests were made in Supersonic Tunnel No. 2 and the Hypersonic Tunnel of the Naval Ordnance Laboratory. The boundary layer on the model was laminar in all cases. The tunnel running conditions were as follows:

Supersonic Tunnel No. 2:

Mach Number	=	3.04
Supply Pressure	=	15.7 to 34.7 lb/in^2 abs.
Supply Temperature	=	59 to 68°F
Reynolds Number per foot	=	2.6×10^6 to 5.8×10^6
Reynolds number based on diameter	=	0.87×10^6 to 1.93×10^6

Hypersonic Tunnel:

Mach Number	=	5.98
Supply Pressure	=	177 to 444 lb/in^2 abs.
Supply Temperature	=	631 to 667°F
Reynolds Number per foot	=	2.3×10^6 to 5.5×10^6
Reynolds Number based on diameter	=	0.77×10^6 to 1.83×10^6

Instrumentation

Figure 3 is a schematic diagram of the pressure instrumentation setup. Each pressure tap is connected to a pressure transducer by stainless steel tubing. The transducer is mounted is a pressure switch capable of holding 48 transducers and switching each one from model to calibration pressures. The electrical signal from the transducer is recorded on magnetic tape by the DARE data readout system. This system is capable of continuously recording 100 inputs per second. At the same time two pressure taps are monitored on plotters. These two pressure taps are at the same r location 180 degrees apart and are used to aerodynamically align the model.

Two brands of transducers are used. They are the CEC 312 and the Statham 130. For the pressures on the windward half of the model, 0 to 15 psia transducers are used, whereas the pressures on the leeward half were read on 0 to 5 psia transducers.

Experimental Procedure

The experimental procedure was essentially the same for both wind tunnel tests. The model was oriented in the test section so that all of the pressure taps lie in the same pitch plane. Then all pressure tube connections were made and the pressure measuring system was checked for leaks. Immediately before each data run was made, each transducer was calibrated at values of 0, 0.5, 1.0, 10.0 and 15.0 lb/in^2 absolute.

During each data run the following steps were followed:

1. Supply pressure and temperature were stabilized at the desired value.

2. Pressures recorded on the two plotters were observed. If the model is aligned with the flow these pressures will be equal.

3. The data were continuously recorded on magnetic tape for approximately 10 seconds giving 10 data points for each tap.

4. While the pressure data were being recorded, schlieren pictures of the flow field were photographed.

Possible Sources of Error

Measurements of the model contour were made after the tests and these measurements were not identical to the design values. Table I gives the measured and design values of the contours. As can be seen, the error in the contour becomes greater as r increases and the maximum absolute error in z is 0.007 inches. These small errors give a model that is a little more blunt. Based on a Newtonian pressure distribution, the error is less than 1.5 percent.

The sensitivity of the data readout system was better than one percent.

The transducers used were stable with time. Drift from calibration to calibration was no more than 0.5 percent for 95 percent of the transducers and none drifted more than 2.0 percent.

The gages used to read the calibration pressures are less than 0.5 percent in error.

The model was not in exact alignment with the flow. For the M = 3 and M = 6 data the percent pressure difference due to misalignment was up to 1.0 percent and 2.0 percent, respectively.

Therefore, the pressure error due to misalignment is not more than 0.5 percent and 1.0 percent for the M = 3 and M = 6 data, respectively.

The schlieren photographs of the shock shape were made with 70 millimeter black and white film. The expected dimensional change of this film is less than 0.2 percent. This is well below the measurement errors. Quantitative measurements of the shock shape were obtained by reading the negatives on a telereader. The telereader gave from 100 to 125 counts between the shock and the body, and a measurement between two clearly defined points could be made to within one count. The degree of scatter of these measurements is caused by the poor definition of the shock.

Data Reduction

Pressure

Before reducing the data the pressure calibrations of each transducer were plotted and found to be linear in the range of pressures encountered during the tests. Then each pressure measurement was reduced by linear interpolation between the two nearest calibration points.

Shock Shape

The shock shape was measured on a telereader. This instrument projects the negative on a frosted screen through an optical system. Superimposed over the negative's image were vertical and horizontal cross-hairs. The negative was adjusted so that the model was aligned with the cross-hairs and the telereader was zeroed at the stagnation point. The z position of the shock model was measured for various values of r and the corresponding count readings were punched on data cards. Then these counts were reduced to inches on the IBM 7090 computer.

RESULTS

Pressure

Table 2 contains a list of the pressure measurements for both M = 3.04 and M = 5.98 data. The pressure data are ratioed to $\rho_\infty u_\infty^2$ and the model coordinates are made dimensionless with respect to the radius of curvature at the stagnation point (4 inches for this model).

Figure 4 is a plot of the M = 3 pressure data along with several calculated curves. As can be seen, the curves generated by MIT, AVCO, NASA, and NWL are in best agreement with the

experimental data. The curve labeled DOUGLAS 1 follows the experimental data for $0 \leq r \leq 0.35$, then falls slightly below. NORTHROP's calculations are in agreement for $0 \leq r \leq 0.3$.

Presented in Figure 5 is the data for $M \simeq 6$. Again the NASA and NWL curves are in best agreement along with the DOUGLAS 1 and DOUGLAS 2 curves. The calculated values of NORTHROP are in good agreement in the range $0 \leq r \leq 0.325$. Here the MIT and AVCO curves fall somewhat below the experimental data.

The direct method of calculating the flow field is used by MIT, AVCO, and NWL, whereas NASA and DOUGLAS 1 use the inverse method. For a more complete description of the calculated values, see reference (1).

Shock Shape

Figures 6 and 7 are schlieren photographs of the bow wave and model at Mach numbers of 3.04 and 5.98, respectively. The $M = 3.04$ shock shape measurements are compared with the calculated values in Figure 8. The shock shapes generated by NASA, DOUGLAS 1, NWL, NORTHROP, MIT, and AVCO are in best agreement with the experimental data. For the most part, these agreements are consistent with the pressure results.

Due to the increase in the scatter of the shock measurements at $M = 5.98$, the comparisons with calculated values are not as certain as those made with the $M = 3.04$ data. It appears that the results at Mach 5.98 are very similar to those at Mach 3.04.

CONCLUSIONS

The results of experimental static pressure and shock shape measurements on an oblate shperoid have been presented. These results show that the calculations of NASA, DOUGLAS 1, and NWL are consistently in good agreement with the experimental data. Also, the predictions of NORTHROP are in good agreement with experiments from the stagnation point to $r = 0.3$.

REFERENCE

(1) Perry, J., "A Comparison of Solutions to Some Blunt Body Problems," to be published as a report by the U. S. Naval Weapons Laboratory, Dahlgren, Virginia

TABLE 1

COMPARISON BETWEEN MEASURED AND DESIRED MODEL CONTOUR

R (in.)	Measured Z_* (in.)	Design Z (in.)	$Z - Z_*$ (in.)
0	0	0	0
.1	.0010	.0010	0
.2	.0046	.0040	-.0006
.3	.0107	.0110	.0003
.4	.0169	.0200	.0004
.5	.0308	.0320	.0012
.6	.0449	.0460	.0011
.7	.0617	.0630	.0013
.8	.0818	.0840	.0022
.9	.1048	.1060	.0012
1.0	.1316	.1340	.0024
1.1	.1622	.1640	.0018
1.2	.1969	.2000	.0031
1.3	.2366	.2400	.0034
1.4	.2824	.2860	.0036
1.5	.3349	.3380	.0031
1.6	.3953	.4000	.0074
1.7		.4980	
1.8	.5585	.5640	.0055
1.9	.6807	.6880	.0073
2.0	-	1.0000	

TABLE 2

EXPERIMENTAL PRESSURE DISTRIBUTION ON AN OBLATE SPHEROID

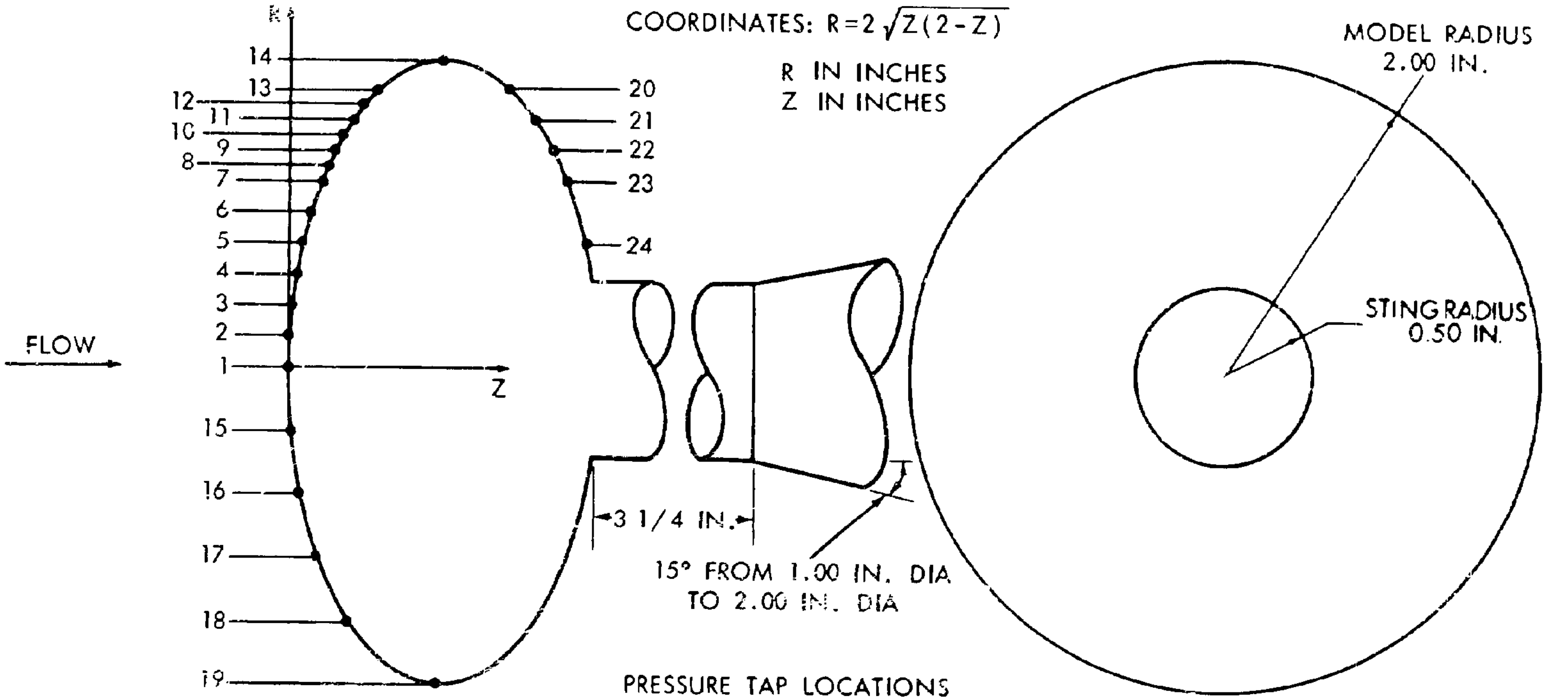
Bluntness Parameter B = 4
Radius of Curvature at Stagnation Point, R_c = 4 inches
Maximum Diameter = 4 inches

M = 5.98
p_o = 443.6 lb/in² abs.
T_o = 631°F
Re_D = 1.92×10^6

r	p $\phi=0^\circ$	p $\phi=180^\circ$	p Leeward $\phi=0^\circ$
0	.930		
0.050	.928		
0.100	.914	.910	
0.150			
0.200	.868	.874	.0169
0.250	.821		
0.300	.764	.780	.0163
0.325	.720		
0.350	.675		.0167
0.375	.626		
0.400	.558	.568	.0163
0.425	.475		
0.450	.378		.0164
0.500	.043	.043	

M = 3.04
p_o = 31.1 lb/in² abs.
T_o = 68°F
Re_D = 1.70×10^6

r	p $\phi=0^\circ$	p $\phi=180^\circ$	p Leeward $\phi=0^\circ$
0	.956		
0.050	.955		
0.100	.943		
0.150	.919		
0.200	.882		.0374
0.250			
0.300	.794	.801	.0355
0.325	.757		
0.350	.708		.0398
0.375	.661		
0.400	.598	.596	.0381
0.425	.514		
0.450	.405		.0372
0.500	.052	.050	



PRESSURE TAP LOCATIONS

TAP NO.	R	Z	TAP NO.	R	Z
	INCHES			INCHES	
1	0	0	13	1.800	0.564
2	0.200	0.004	14	2.000	1.000
3	0.400	0.020	15	-0.400	0.020
4	0.600	0.046	16	-0.800	0.084
5	0.800	0.084	17	-1.200	0.200
6	1.000	0.134	18	-1.600	0.400
7	1.200	0.200	19	-2.000	1.000
8	1.300	0.240	20	1.800	1.436
9	1.400	0.286	21	1.600	1.600
10	1.500	0.338	22	1.400	1.714
11	1.600	0.400	23	1.200	1.800
12	1.700	0.472	24	0.800	1.916

FIG. 1 SKETCH OF THE OBLATE SPHEROID SHOWING PRESSURE TAP LOCATIONS

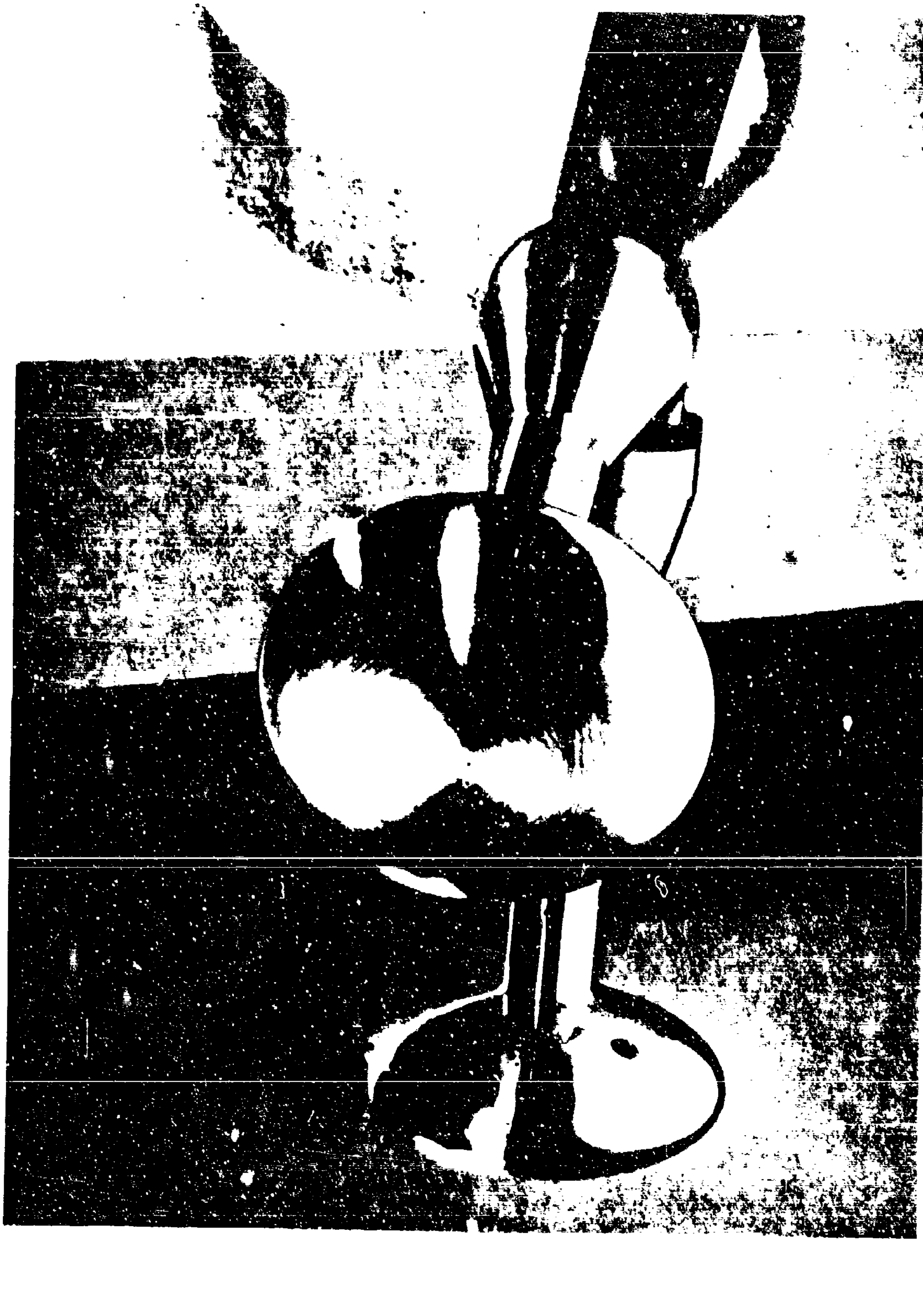


FIG. 2 PHOTOGRAPH OF THE OBLATE SPHEROID MODEL

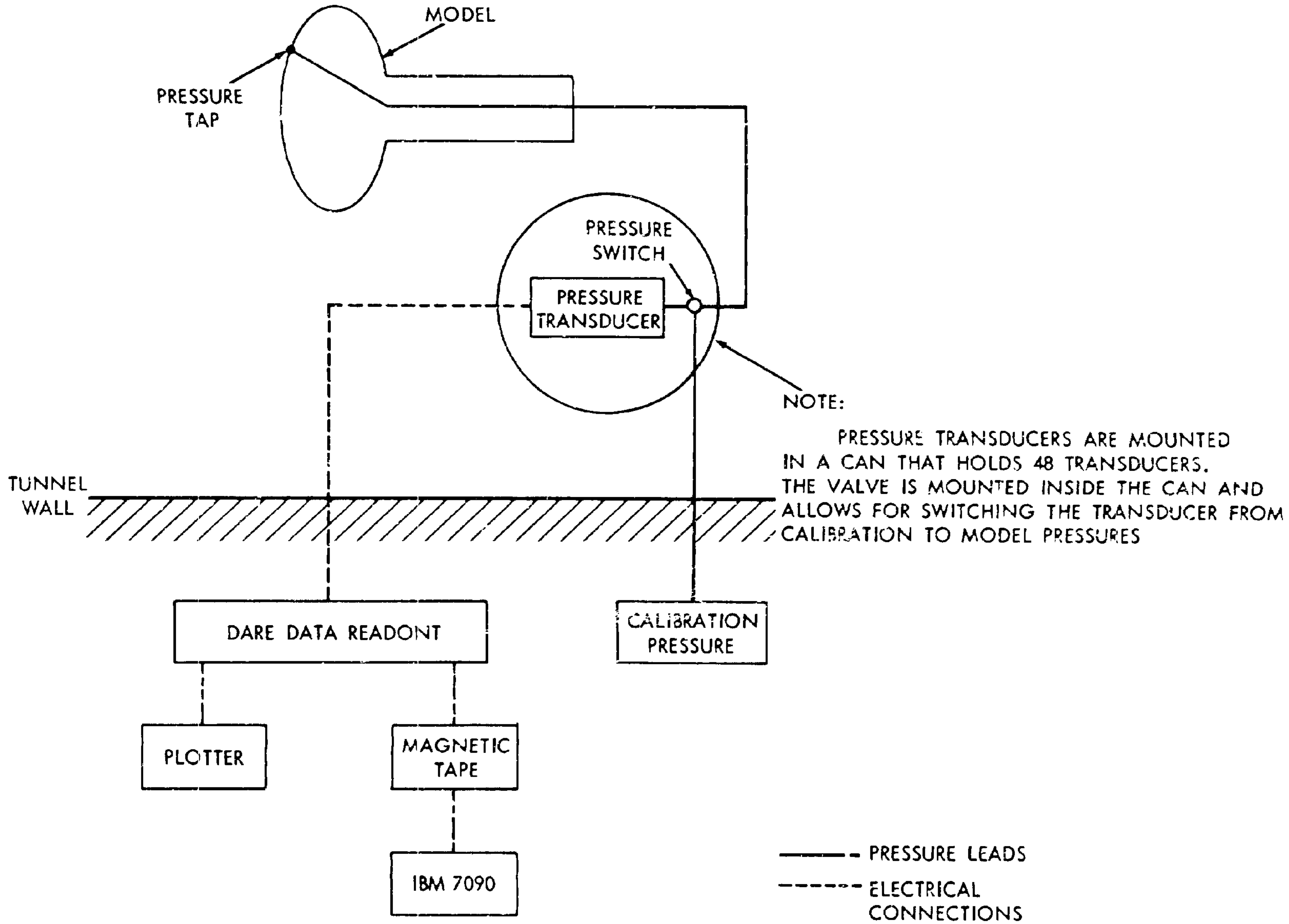


FIG. 2 SCHEMATIC DIAGRAM OF THE TEST SET-UP

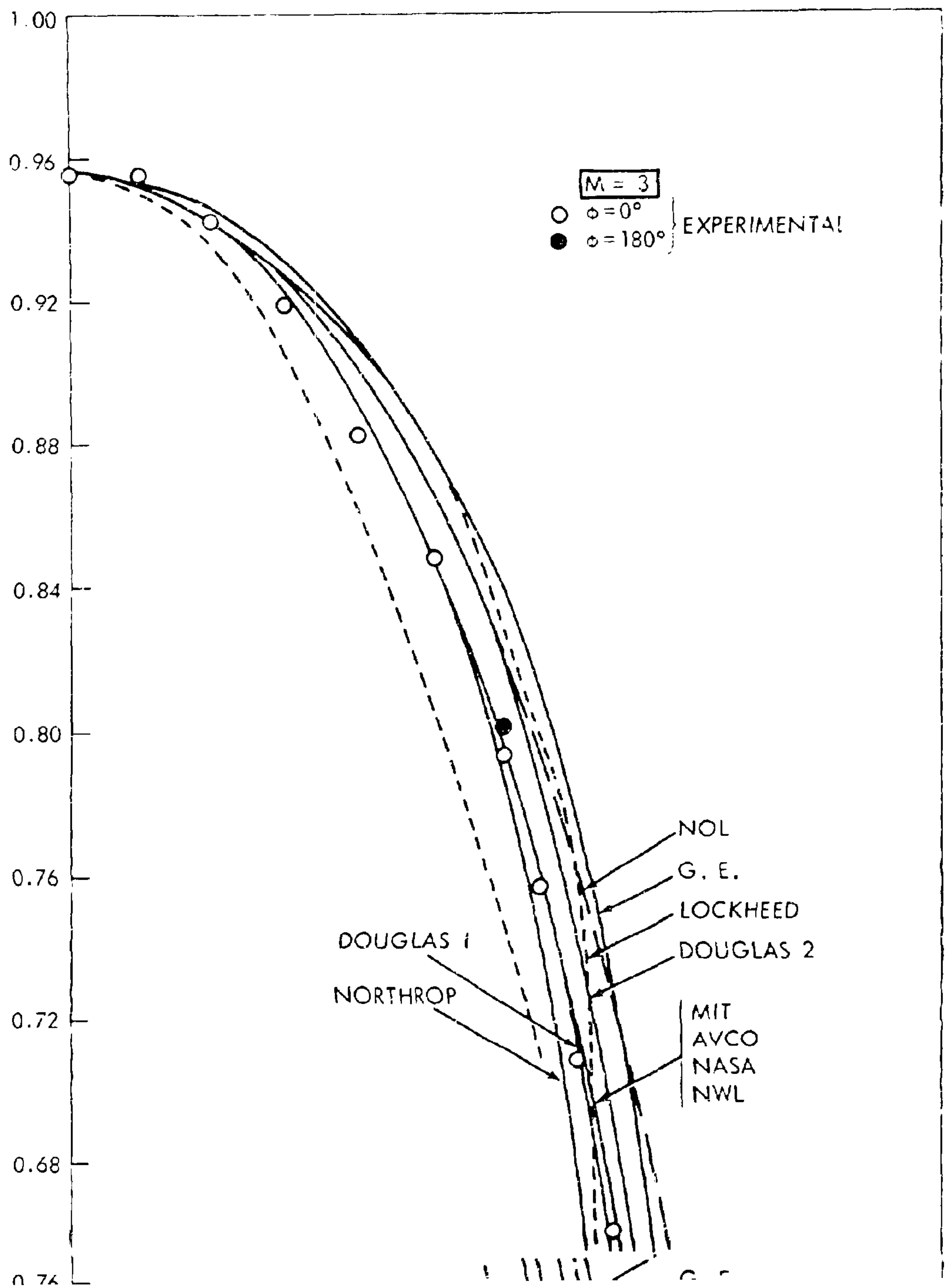

1.00
0.96
0.92
0.88
0.84
0.80
0.76
0.72
0.68
M = 3
$\phi = 0°$
$\phi = 180°$
EXPERIMENTAL
NOL
G. E.
LOCKHEED
DOUGLAS 2
DOUGLAS 1
NORTHROP
MIT
AVCO
NASA
NWL

FIG.

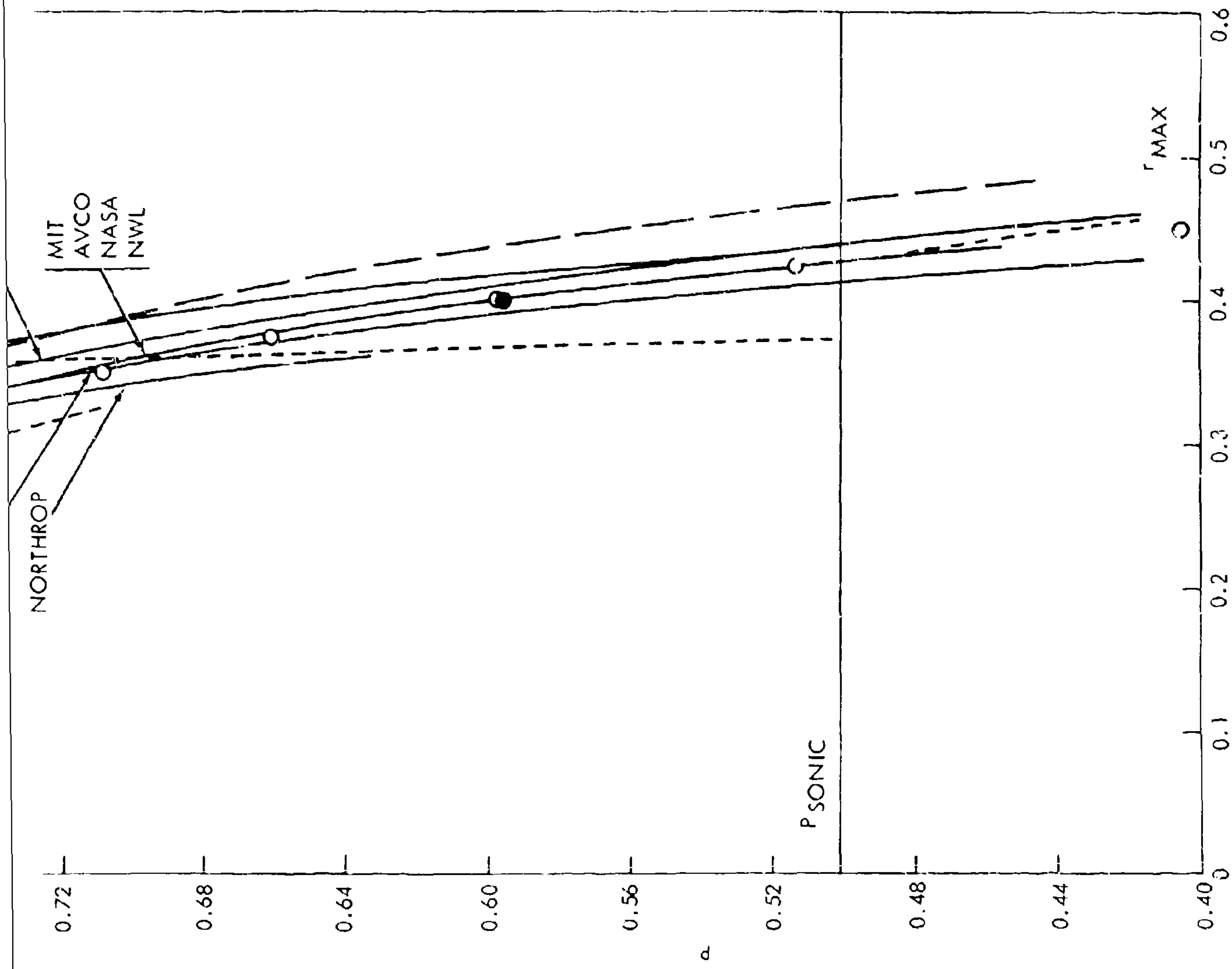
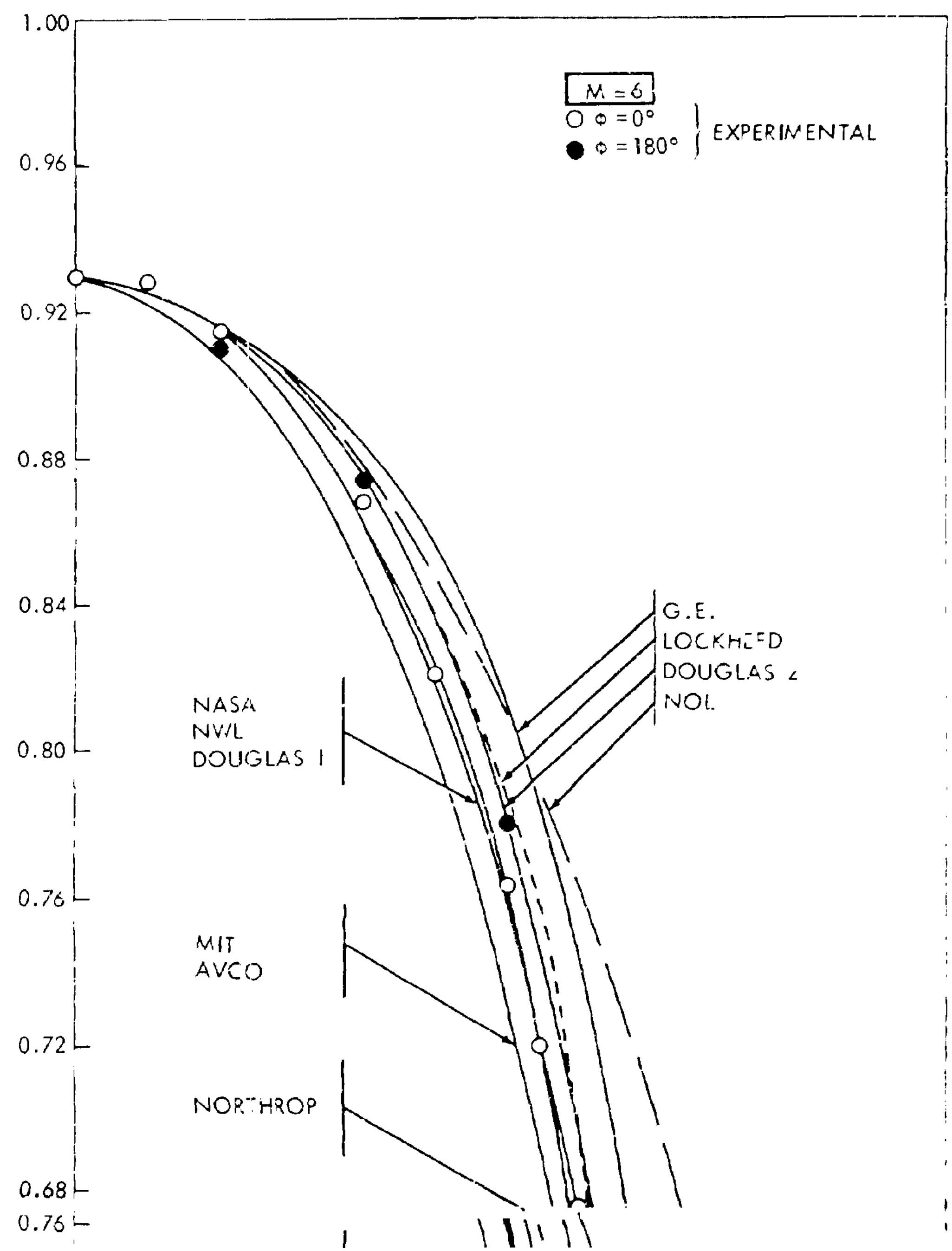


FIG. 4 COMPARISON BETWEEN THE EXPERIMENTAL AND CALCULATED VALUES OF THE SURFACE PRESSURE ON THE OBLATE SPHEROID MODEAL AT M ≈ 3.



1.00
0.96
0.92
0.88
0.84
0.80
0.76
0.72
0.68
0.76
M = 6
○ Φ = 0°
● Φ = 180°
EXPERIMENTAL
G.E.
LOCKHEED
DOUGLAS 2
NOL
NASA
NWL
DOUGLAS I
MIT
AVCO
NORTHROP

A

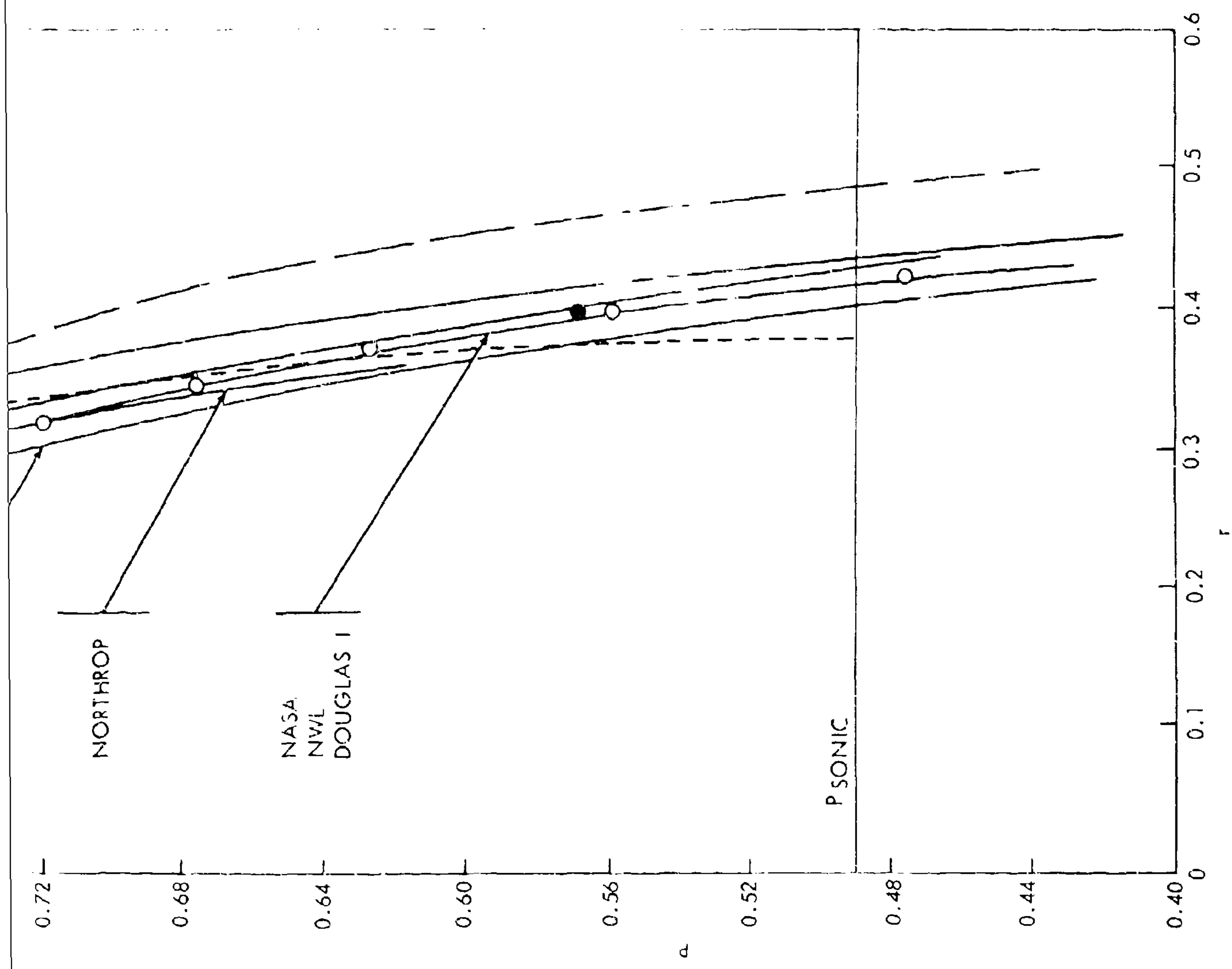


FIG. 5 COMPARISON BETWEEN THE EXPERIMENTAL AND CALCULATED VALUES OF THE SURFACE PRESSURE ON THE OBLATE SPHEROID MODEL AT M = 6

B

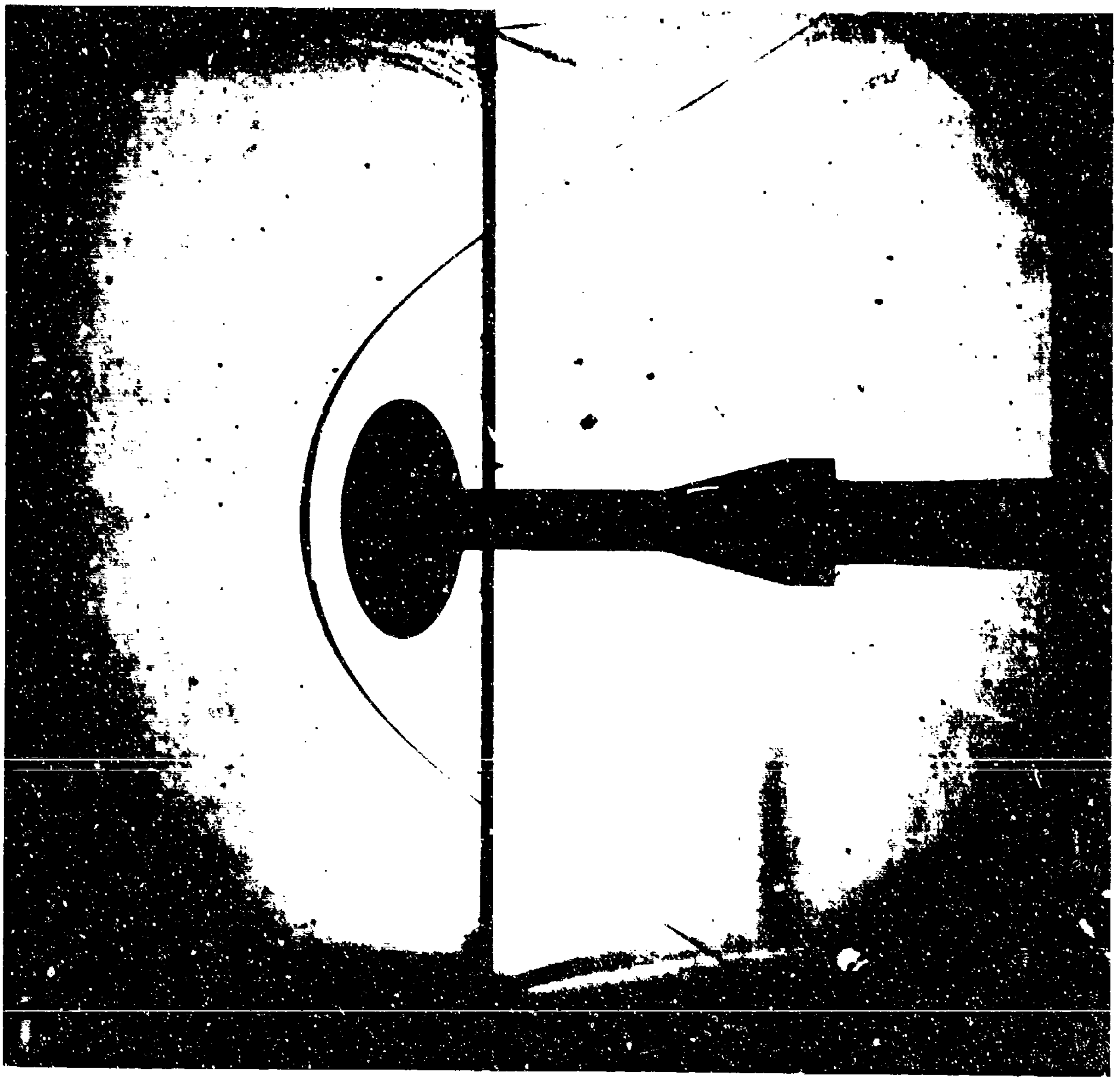


FIG. 6 SCHLIEREN PHOTOGRAPH OF THE SHOCK WAVE AND MODEL AT $M = 3$

FIG. [illegible] SCHLIEREN PHOTOGRAPH OF THE SHOCK WAVE AND MODEL AT M = [illegible]

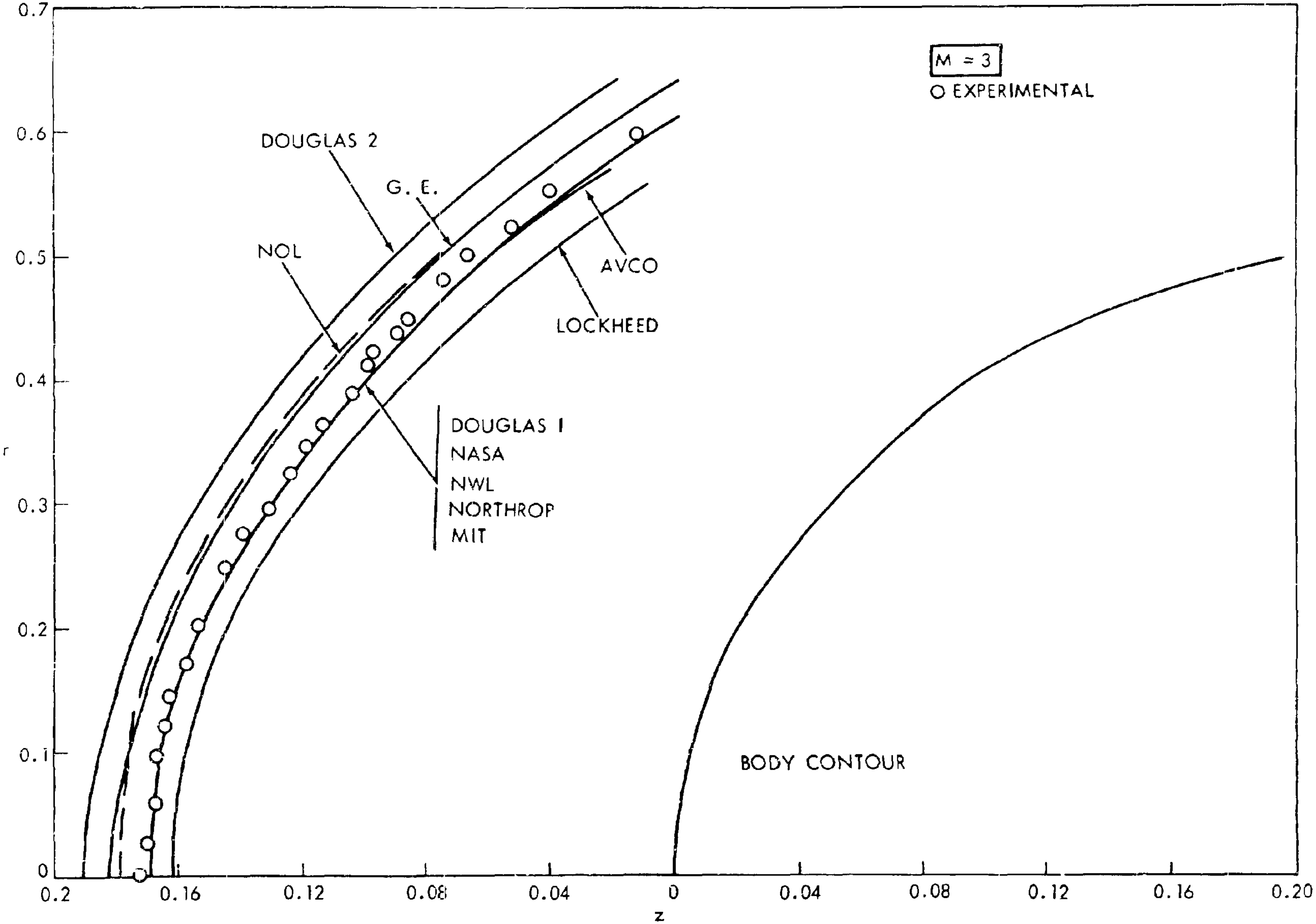


FIG. 8 COMPARISON BETWEEN THE EXPERIMENTAL AND CALCULATED VALUES OF THE SHOCK WAVE PRODUCED BY THE OBLATE SPHERIOD MODEL AT M = 3.

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